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# A systematic approach to analyzing environmental issues involving complex systems (a web-based course)

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***Abstract*** *- The course "Conceptual Modeling for Decision Support" (Univ. Gothenburg, Sweden) is a web-based course, given the first time in October 2015. This introduction and other supporting documents on the website intend to provide a background for independent work with the five tutorials that comprise the core of this course. The openly accessible website will allow study at any time, but can ideally be combined with the blended-learning course in "Environmental Geology" or with project work at various institutes in the relevant cooperation networks. The introduction below develops both the philosophical and the practical framework for modeling environmental systems. Differences in scale, time and the complexity are necessary to consider when evaluating the parameters within the system, but modeling is also an attempt to simplify in order to understand the net effects of the combined components. Multi-criteria evaluation allows predictive modelling by combining the typically qualitative and quantitative information from multidisciplinary sources. The course structure and tutorials are briefly presented.*

***Keywords*** *– environment, modeling, multi-criteria evaluation, system analysis, web-based course*

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## Introduction

This is short introduction to the concept of utilizing the illustrative capacity of modeling to understand processes and decision-supporting scenarios common in Environmental Sciences. The basic idea involves the employment of problem-based learning to examine complex environmental systems at both large and small scales. At large scales the emphasis is placed on the processes within a system and any existing trends. For small-scale systems the focus is given to the characterizations and importance of parameters that describe a system. The course-related tutorials presented after this introduction provide some tools for conceptual modeling of complex environmental systems and their their application.

A conceptual model is a generalization of a system consisting of various levels of complexity. Such a system can be a single object that contains multiple parts. Conceptual models consist of a series of concepts that facilitates the scientific understanding of the system being studied. In doing so, we can therefore forecast changes to the system in response to a particular event or perturbation. Furthermore, conceptual models may be physical in nature and may range from simple (containing few components) to complex (containing multiple components). This introduction attempts to be general and therefore is far from complete and comprehensive. Furthermore, it is intended to be supplemented by lectures. Much of the following is based on the following books: Leopold (1971), Hardisty et al. (1993), Scholz and Tieje (2002), Landis, (2004) and Vester, (2007).

## The Environment: From large to small scale

Our planet is the cradle to life, as we know it. Earth is the third planet from the sun and resides in the so-called "Goldilocks Zone" where conditions, with regards to the radiation exchange between a planet and its parent star, are conducive to life. When considering the environment that life on Earth calls home, our plant's location in the solar system is generally the starting point in understanding this environment as it sets the outer boundaries for conditions necessary for life to thrive in a harmonic and sustainable balance. As we move from the celestial scale to smaller and smaller scales we find that the conditions that control the planet's air quality, near-surface temperature, precipitation and other characteristics are intricately and inextricably intertwined, complex. Also, these conditions enjoy a balance that, while robust, can easily be perturbed and/or destroyed. Also, as we change scales, the apparent complexity of the system can become simpler or more complex, perhaps largely depending upon the extent of observations.

The environment is a natural concern for the life forms living in it. In the past mankind have always been subject to the whims and nuances of nature. This is perhaps why we today often see the natural environment as an enemy, something to be exploited rather than sustained. From the cold Arctic and Antarctic regions to the sweltering heat of the Tropics, the various environments have helped to shape mankind and mold him into what we see across the planet today. Therefore, environmental problems should be of paramount concern for humans as we stand atop the food chain as perhaps

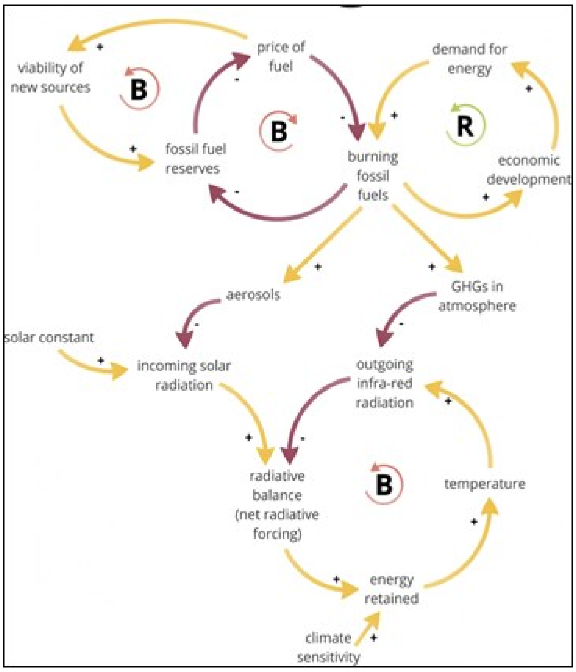


**Figure 1.** An example of the human fossil energy system interacting with the planet's climate system. The yellow arrows are positive forcing (+), the red arrows are negative forcing that dampens the system (-). Sub-systems in balance are denoted with a B while positive feedbacks that reinforce a perturbation are marked with an R. Source: [http://www.easterbrook.ca/steve/2013/08/the-climate-as-a-system-part-3-greenhouse-gases/](http://www.easterbrook.ca/steve/2013/08/the-climate-as-a-system-part-3-greenhouse-gases/)

the most vulnerable of the planets' inhabitants.

Since the industrial revolution, circa 150 years ago, mankind have developed the ability to radically and significantly change/affect the environment. This anthropogenic influence extents to virtually all scales of life: from the microbes of many coastline estuaries to the acidity level of the world's oceans and the ozone layer that protects all life on the planet. As mankind have gone from nomadic tribes to settled communities, which then exploded into nation states, it has reached a level where the combined affects of industrialization and urbanization have caused major environmental issues. At this level of exploitation land, transportation of goods, water management (or the lack thereof), and the use of fossil fuels, to name a few, have been linked to cause of serious environmental issues. Figure 1 is an illustration of how the planet's climate system interacts with the use of fossil fuels to bring about a change in the system (increased global temperature, ocean acidification, pollution, deforestation, etc.). The yellow arrows depict positive impacts (+), and the red arrows show negative impacts (**-**). A balance within a subsystem is given the letter, **B**, and when a perturbation is reinforced by a positive feedback loop in a subsystem, it is depicted with an **R**. On a much smaller scale, but never the less involving similar complexity, Figure 2 show a coastal ecosystem (2 estuaries) near Gothenburg. The land, rivers and sea areas interact to provide diverse habitats for both land-based and ocean-based plants and animals. Therefore, activities on land and in the ocean will both affect such ecosystems.

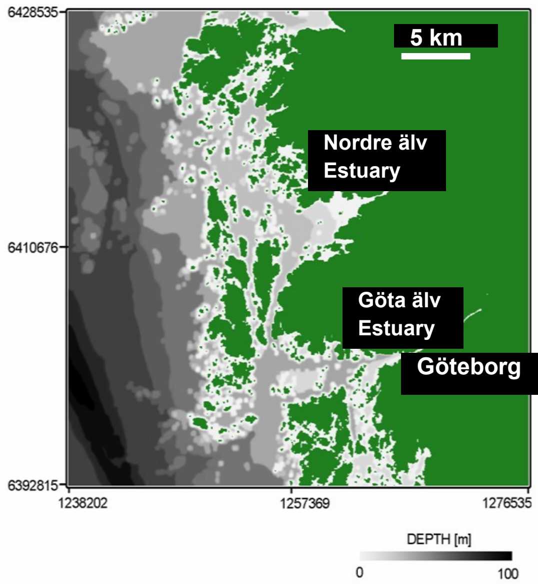


**Figure 2.** *The Göta älv River (SW Sweden) has two distributary estuaries. These drowned river valleys and the archipelago reflect the immature character of the emergent coast, where depocenters are progressively moved eastward during forced regression.*

## Environmental Systems

The study of understanding environmental systems involves a high level of abstraction. In this subject the physical, chemical and biological laws provide rules for understanding the interaction of the approximated processes.

Integrated environmental systems are different in many ways from the isolated objects of study in physics and chemistry though the integrated study of the environment cannot take place without the building blocks provided by research in physics and chemistry. Environmental systems are characteristically:

**Large-scale and long-term**: Despite the spatial and temporal scales of the region being studied, all environments on the planet fit within the large system that is continuously evolving. Any and all environments being studied, no matter the scale, must share material and energy with this larger system. Although they appear to act independently, they must be seen with this greater context as well.

**Multicomponent**: There are rarely systems that have just one or two processes that are appropriate to model. The nature of many environmental systems is that they are the result of multiple subcomponents (living or nonliving) and have therefore many interacting processes. An inherent consequent of a system's multicomponent nature is the difficulty that arises when identifying cause and effect.

**Real world conditions**: Environmental systems cannot be controlled. It is not possible to test the impact of individual perturbations while keeping all other conditions constant. Also, the complex nature of the system makes it difficult to reproduce it in a lab.

**Multiscale and multidisciplinary**: Processes interacting on multiple scales is a characteristic inherent to many environment systems. Within the atmosphere, for example, processes occur on time scales from microseconds to weeks, and on length scales from millimeter to thousands of kilometers. Furthermore, the atmosphere interacts with the ocean, the ocean interacts with the biosphere, the lithosphere interacts with the ocean and the atmosphere, and other similar connections. No one discipline, no one subject covers all of these areas, therefore, environmental science is multidisciplinary.

**Multivariate and nonlinear**: The emergent properties of an environmental system are dependent upon a myriad of independent variables with complex interactions. This property makes the system nonlinear and complex.

## Modeling Something Complex

The complexity of a system depends on the number of interconnections between the subcomponents or processes necessary to describe the system. Such systems display emergent behaviors, and within a complex system, the effects and outcome are usually observable features, but not the processes. An ideal model of complex systems is one that contains sufficient complexity to reasonably explain key phenomena of the system. It is important to find the optimal number of processes for a simple and descriptive model that will not be difficult to handle and evaluate.

The elements of a system are analyzed and only those that are thought to be important in explaining the observed phenomena are retained within the model. This is called a reductionist approach. However, this approach quickly leads to overly complex models whose complexity is roughly inversely proportional to the fidelity of the results. A major drawback of the above approach is its limited ability to represent certain real-world processes, a constraint brought about, among other things, poor scientific understanding of the processes being described. Another approach to modeling complex systems revolves around keeping the governing equations for the simulated processes describing the system simple. This approach is more holistic in nature and offers more realistic representation of the interactions between the processes within the system.

The aforementioned approaches, when expressed numerically and applied to real world systems, tend to be computationally demanding, but produce more objective results that are emergent: arising from the interactions of the various describing processes. The modeling approach in this case is one of deciding what level of simplicity in model structure is required relative to the overall costs and the desired explanation or understanding.

Models can be used to evaluate whether effects and outcome are reproducible from the current knowledge of the active processes in the system. Such an evaluation is not straightforward, as it is often difficult to evaluate whether process or parameter estimates are correct, but it does at least provide a basis for investigation. Models provide a qualitative description, or a numerical simulation, in order to understand the outcome of a particular perturbation to the system.

Modeling is not an alternative to observation but, under certain circumstances, can be a powerful tool in understanding observations and in developing and testing theory. Observation will always be closer to truth and must remain the most important component of scientific investigation. However, one must remember that no observation is without a degree of uncertainty that depends on the instruments accuracy, precision, and any underlying assumptions used to realize the measurement. A model is therefore an approximation of a real system that helps the user understand the nature and sensitivity of a complex system to changes as well as it facilitates the exploration of hypotheses about the system.

The purpose of modeling can be to simulate and understand the impact of future events, anthropogenic effects on the environment, or the impact of environmental effects on humans. Conceptual models provide a means of deconstructing the complexity of environmental systems and, through experimentation, of understanding the univariate contribution to multivariate complexity. These types of models also explain behaviors of the system based on the level of scientific understanding underpinning the approximation of the processes that describe the system. Figure 3 shows an example of a simple system showing the interaction between the plants, some animals, the soil, and the atmosphere.

## Creating a decision-support model

The structure of a complex system can be modeled

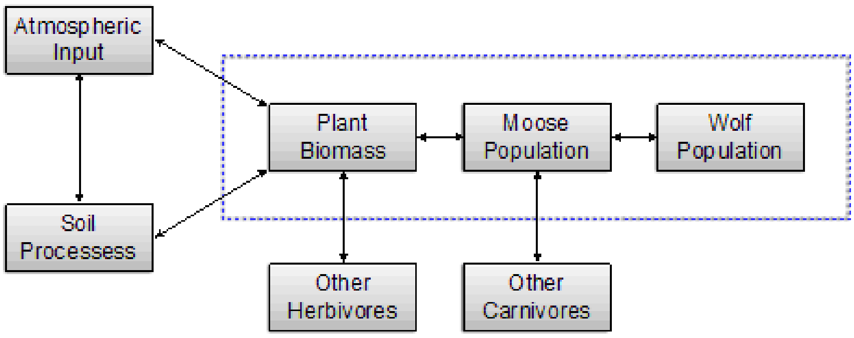


Figure 3. A simplified ecosystem: Ise Royale National Park, Michigan. Hardisty et al. (1993; after Johnson, 1989).

with the following (or similar) interacting operations: 1) Describing the system, 2) Identifying actual variables, 3) Checking for systematic relevance, 4) Studying interactions, 5) Determining role within the system, 6) Examining overall interconnectedness and system dynamics, 7) Weighting preferences and impact of variables, 8) Combing variables to forecast individual scenarios, 9) Evaluating the model, and 10) Formulating strategy. The first steps are largely analytical, where the problem is characterized and subdivided into variables (or criteria) influencing the system. Steps 7 and 8 combine the variables in a model construction.

Analytic and synthetic modeling can ideally be considered as two complementary approaches. The former employs fixed outer boundaries and inexact (parameterization) representation of the relationships and processes in the system it is attempting to approximate (Hudson 1992). This is appropriate when complex environmental systems initially need to be defined from a holistic perspective, while internal relationships are often only partially documented. Analytic modeling breaks apart the system (or problem) into components, a “top-down” approach. Characterization of the properties and interactions of the intrinsic variables (a system analysis) is then successively improved within this conceptual model.

Synthetic modeling uses an understanding of relationships and processes to define these and build predictive models. This can be considered a bottom-up approach whereby the system is represented using its relevant components. Although this approach is most common in engineering fields where variable are previously known, it can also be based upon the analytical modeling of more complex systems, especially if the tools used for synthesis can accommodate different types of information. One such tool is is the Multi-Criteria Evaluation (MCE). Basically, MCE is used to examine choices and possibilities given a set of criterion and objectives. Thus, it is possible with MCE to rank the alternatives. This is particularly useful with evaluating complex problems/systems where multiple views/criteria are in play.

Figure 4 illustrates, with the aid of the Brunswikian Lens scheme (Scholz and Tieje 2002), the combination of analytical and synthetic modeling, typically to support decision-making. Decomposition is analytical (left side), where the problem is clearly defined, broken down, and researched. Then, alternatives or variables are created or identified as well as any constraints, key processes and uncertainties that might exist. Finally, the problem can be framed (boundaries set) and criteria set for the solving the problem. Both analytical and synthetic modelling involve comparative judgements of the criteria when evaluating their internal impact upon each other (system dynamics) and their relative importance for scenario results or ranking of alternatives.

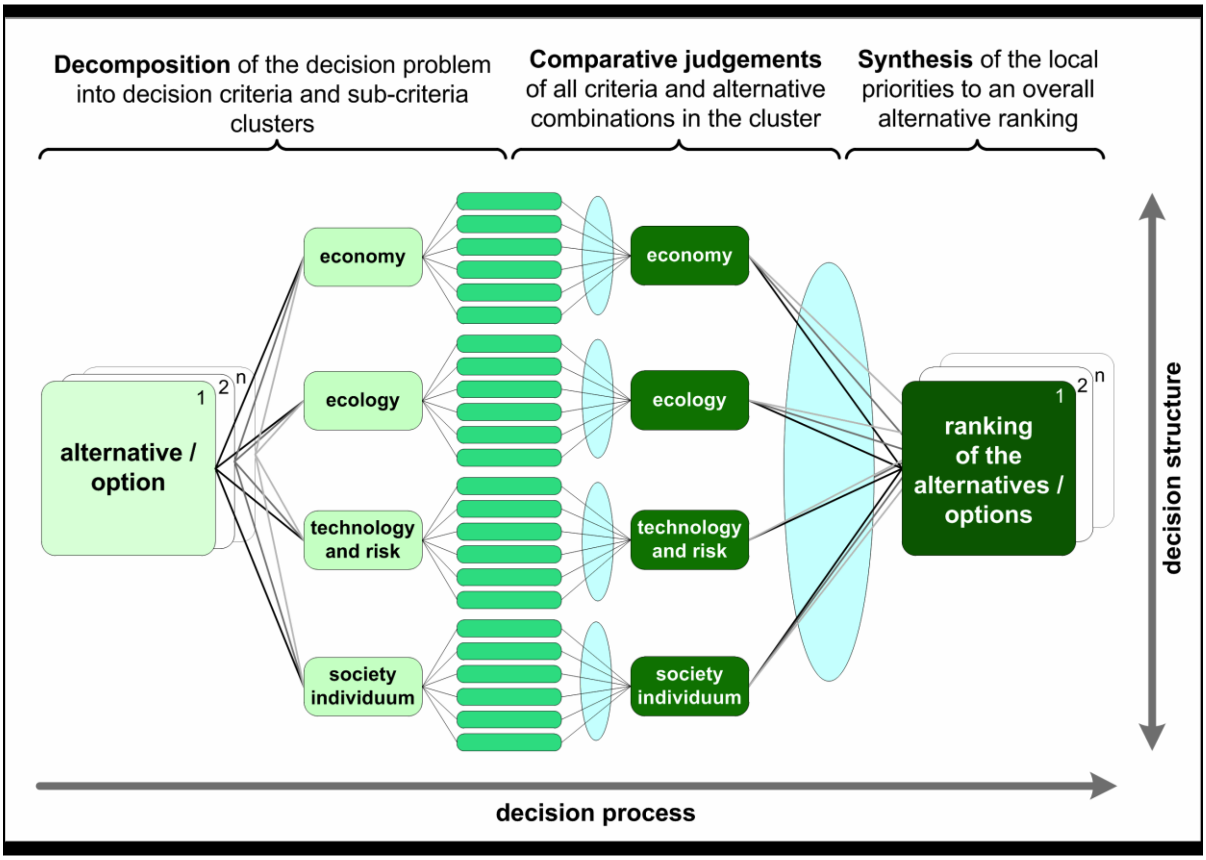


Figure 4. An example of a Brunswikian Lens Model being applied to an analytical hierarchy process. Image source: http://jasss.soc.surrey.ac.uk/14/2/4.html\#scholz2002 (adapted from Scholz and Tietje (2002).

This structured methodology, first analyzing and then constructing a representative model for the system, can in general be applied to a wide range of issues involving complex systems. This evaluation could be a risk assessment of a particular environmental system or about learning how the system works, that is to say, its short- and long-term cycles and its sensitivity to changes. For example, given a sufficient understanding of the system, it would be then possible to judge the possible placement of a factory in or near an environmentally sensitive area, as a decision-supporting model.

When determining the risk some action or intervention might have on a complex system there will always be a degree of uncertainty and some amount of risks. These risks need to be weighted and assessed as to their likely outcome. A risk, probability, or impact matrix is a framework that aids in deciding the greatest risk the problem being examined poses. Similarly, one can replace the word "risk" for "decision" in the text above and the reader should continue to think of these two terms as inter-changeable. A risk can be described by it probability or occurrence and its impact, which is often considered negative. Some important criteria to consider are (i) magnitude of the effect, (ii) degree of change expected, (iii) geographical extent, (iv) significance/importance, and (v) special sensitivity. However, the impact analysis typically includes the definitions of the magnitude and the importance, which will be weighted. The term magnitude is used in the sense of degree, extensiveness, or scale, which can be evaluated factually. A weighting of the importance of the impact on the environment must include a consideration of any consequence that might unfold. The evaluation of the importance, or significance, will be of a more subjective nature.

## A web-based, short course in conceptual modeling

The course “Conceptual Modeling for Decision Support” (Univ. Gothenburg, Sweden; www.rodneystevens.wix.-com/shot1) is a web-based course that was given the first time in October 2015. The successive steps for modeling complex problems are also seen as a problem-based instructional basis with multiple pedagogic advantages. The decision process (cf. Fig. 4) is also mimicked by the sequence of web-based tutorials, shortly described below, and that intend to progress from system understanding to decision support. The first three tutorials do with commonly used and basic tools, whereas the last two (functional facies and risk ranking) are presenting approaches for the complexity that can be expected in many environmental systems.

1. **Environmental sketch.** Defining and describing the system can often be aided by a cartoon sketch that includes the most important variables. A group can use this for brain-storming and to integrate their different perspectives. The objectives and the variables derived here are involved in all subsequent steps, motivating the effort to systemize what many might mistakenly assume was obvious.
2. **System structural analysis.** To study the internal relationships and dynamics of a system, one of the most common methods is by using interaction matrix representing the impact of the variables on each other. The resulting influence and cause-and-effect diagrams visualize the interactions. Identified feedback loops are important.
3. **Multi-criteria evaluation.** Predicting the impact of variables involves each variable’s importance within the system relative to the other variables (the “weight”) and the variable’s actual value within a specific scenario. In a MCE the summed impact of all the variables can be used to predict effects or rank alternatives.
4. **Functional facies.** Since most environmental problems involve complex associations, the facies classification concept can be used to optimize database management and to suggest mapping, sampling, laboratory analyses, evaluation strategies and decision-support application
5. **Risk ranking.** It is seldom possible or realistic to separately consider one relationship and process effect in complex settings. One possible simplification is use of relative comparisons of the variables, such as those for sources, stressors and habitats in an environmental problem.

Although the course materials on allow independent study, the connection to a regularly offered course in Environmental Geology (currently in January-March each year) will make it possible to improve and adapt the tutorials to new problems connected with the cooperation network. The generic character of these tools allows their application to decision support for most any complex problem. Examples and more detailed presentations are found on the website given above, as well as in the references provided here. The course leader can also be contacted directly (stevens@gvc.gu.se).

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